2   RADIATION TRANSPORT AND DOSIMETRY

2.1 OVERVIEW

Paul Goldhagen

In the Radiation Transport and Dosimetry program, analytical and experimental techniques are applied to determine the basic physical properties of radiation fields in the workplace and in the environment. Projects within this program are often initiated in response to requests to properly evaluate occupational radiation exposure problems at DOE facilities or to provide critical exposure assessments for DOE or other agencies. These situations usually involve complex radiation fields containing neutrons and/or high-energy particles for which normal dosimetric techniques are either inadequate or questionable in the absence of adequate validation. We develop, use and provide reliable experimental and theoretical/calculational tools to evaluate the nature, magnitude, and potential health consequences of human exposure to such ionizing radiation. To do so, interactions are maintained with other advanced dosimetry research programs in the U. S. and in other countries. Progress in this program contributes toward establishing a viable risk-based system for radiation protection, one that will have a beneficial impact on the conduct of DOE operations.

The evaluation, application, and development of computer codes for radiation transport (the propagation of radiation, including its interactions with matter) and for spectral unfolding are an important part of this program. Using such codes, calculations are performed to determine radiation fields from instrument readings, to relate measured fields to the properties and distributions of radiation sources, and to interpret the measurements in terms of dose to man. In many cases, calculations provide the basic information on radiation field properties, with critical measurements providing validation.

The experimental part of this program has concentrated on neutron dosimetry because of the continuing difficulties associated with making reliable assessments of neutron fields and exposures. Highly conservative estimates of neutron dose equivalents, which must be used when measurements are uncertain, affect the efficiency and cost of DOE facility operations. Because of the experience gained and expertise developed at EML in this field, notably with multisphere neutron spectrometer (MNS) systems, the Laboratory has responded to a number of requests to provide reference neutron energy spectra at critical locations in or near nuclear facilities and to assess the neutron component and its contributions to dose in complex radiation fields. The long-term measurements at the Princeton Tokamak Fusion Test Reactor (TFTR), described in Summary No. 2.2, have helped assure that the TFTR shielding would be adequate for high-power operation and will contribute to accurate shielding calculations for the next generation of fusion reactors. Neutron spectrum measurements at the Army Pulse Radiation Facility (APRF) (see Summary No. 2.3) were performed at the request of the Defense Nuclear Agency. This study is part of the broad effort to resolve the discrepancy between measured and calculated thermal neutron activation at Hiroshima, one of the most important unsolved problems in radiation dosimetry. In support of our neutron spectrometry measurements, we have changed and clarified our methods of unfolding neutron spectra from MNS data (see Summary No. 2.4) and are calculating the energy response of our new high-sensitivity MNS (see

Summary No. 2.5).

There is increasing awareness that aircraft crews are exposed to secondary cosmic radiation and receive one of the highest average dose equivalents of any occupationally exposed group. However, the atmospheric ionizing radiation field is highly complex, and there is significant uncertainty in our knowledge of the high-energy neutron component, which can cause up to half or more of the biological damage. Because of EML's expertise in neutron spectrometry, the Royal Military College of Canada and the Defense Research Establishment, Ottawa, invited us to join them in performing detailed measurements of the cosmic radiation field aboard dedicated flights of Canadian Forces aircraft. These measurements are described in Summary No. 2.6. The National Aeronautics and Space Administration (NASA) is now considering designs for future high-speed high-altitude civil aircraft in which crews would be exposed to significantly higher levels of radiation. In response to concerns about radiation safety for such aircraft, NASA's Langley Research Center (LaRC) and EML have planned a series of high-altitude measurements of atmospheric ionizing radiation (AIR) using the NASA ER-2 (enhanced U-2) aircraft. The primary instruments will be the ones EML used on the Canadian flights, but a number of other radiation measurement groups will also participate. The AIR project is described in Summary No. 2.7.

Dosimetry systems which are *not* sensitive to neutrons are also important for measurements in complex radiation fields. A study to improve our understanding of the response to neutrons of various thermoluminescent dosimeter (TLD) materials primarily sensitive to low-LET radiation is described in Summary No. 2.8.

Although this program primarily involves research in support of radiation protection activities, it also provides basic scientific information needed for the development of the next generation of radiation protection instrumentation and methods. Thus, this research, while finding direct application to current practical problems of concern to DOE and other government agencies, also has a broad generic value to the radiation protection community and is likely to facilitate the development of improved risk estimates for high-energy and high-LET radiation exposures.

Much of the work in this program involves varying degrees of collaboration with other research and radiation protection groups. Among them, in 1995, have been the Princeton Plasma Physics Laboratory, APRF, Science Applications International Corporation, NASA LaRC, the University of Akron, Los Alamos National Laboratory, the Royal Military College of Canada, and the Defense Research Establishment, Ottawa. For the AIR project, new collaborations have been initiated with the German Air and Space Research Institute (DLR) and Kiel University, the National Radiation Protection Board of Britain, the University of San Francisco, the Boeing Company, the NASA Johnson Space Center, and Apfel Enterprises.

2.2 MEASUREMENT OF LEAKAGE NEUTRON SPECTRA OUTSIDE THE SHIELDING OF THE TOKAMAK FUSION TEST REACTOR

Paul Goldhagen, Marcel Reginatto, Peter Shebell,
William Van Steveninck, and Alfred J. Cavallo

The Tokamak Fusion Test Reactor (TFTR) of the Princeton Plasma Physics Laboratory (PPPL) has been the flagship of America's magnetic-confinement fusion program. In 1994 and 1995, it produced record-breaking pulses of fusion power (>10 MW) using the deuterium-tritium (D-T) reaction. This achievement followed years of development and testing using the lower energy deuterium-deuterium (D-D) reaction. Since 1990, in collaboration with Henry Kugel of PPPL, we have been measuring neutron and gamma radiation field quantities at designated locations around the TFTR.

The EML measurements were undertaken at the request of PPPL to calibrate measurements by TFTR staff, provide benchmark data for shielding calculations, and assure that radiation protection limits would not be exceeded when D-T operation began. The TFTR shielding design objective for the PPPL property lines is to limit the dose equivalent to 0.1 mSv yr^{-1} from all sources and pathways. Our early D-D measurements showed that the TFTR shielding would be adequate to meet this objective during planned D-T operations yielding 1×10^{21} D-T neutrons per year.

Neutron measurements were performed using a multisphere neutron spectrometer (MNS) with 12 detectors operating simultaneously. The spectrometer incorporated computer-controlled gated electronics to allow analysis of individual TFTR fusion pulses (~1 second duration, 7 to 15 minutes apart). In addition, data were collected during the time between TFTR pulses and recorded separately to measure the spectrum of background cosmic-ray neutrons. Measurements were performed 1 m outside the north wall of the Test Cell (about 20 m from the center of TFTR) and 120 m north-northeast of the center of TFTR in a trailer near the site boundary fence. Gamma-ray measurements were also made at these and other locations (Kugel, et al., 1995). Data from more than 8,000 TFTR pulses have been recorded, which is more than enough to determine neutron spectra near the shielding for D-D fusion and at both locations for D-T fusion, but we are continuing our measurements at the 120 m location in order to characterize the change in the radiation field as the fraction of D-T fusion varies from near 1% (D-D operation) to nearly 100% (full-power D-T operation), an important consideration in the design of future fusion reactors and their shielding.

Normalized neutron energy spectra (fraction of fluence as a function of energy) were unfolded from the MNS measurements as described in Summary No. 2.4 and are shown in Figure 2.1. As is customary for neutron spectra displayed on a logarithmic energy scale, the fluence per lethargy is plotted, where lethargy is the natural logarithm of the energy. On such a plot, the typical moderated neutron spectrum (fluence per energy proportional to 1/E) is a horizontal line and equal areas represent equal numbers of neutrons. As expected, the neutrons escaping from the shielding for D-T fusion have higher energies than for D-D fusion, but neither spectrum shows a significant number of unmoderated fusion neutrons (14.1 MeV for D-T, 2.5 MeV for D-D). The ambient dose equivalent, H^*_{10}, per unit fluence calculated for the D-T spectrum is 2.5 times that for the D-D spectrum. Absolute fluences and dose equivalents per TFTR fusion neutron will be determined when the D-D and D-T neutron yield of each TFTR pulse is determined, sorted and summed.

Results of this work were presented at the Fourth Annual Meeting of the Council on Ionizing Radiation Measurements and Standards, November 28-30, 1995, and at the American Nuclear Society Topical Meeting "Advancements and Applications in Radiation Protection and Shielding", April 21-25, 1996, in Falmouth, MA.

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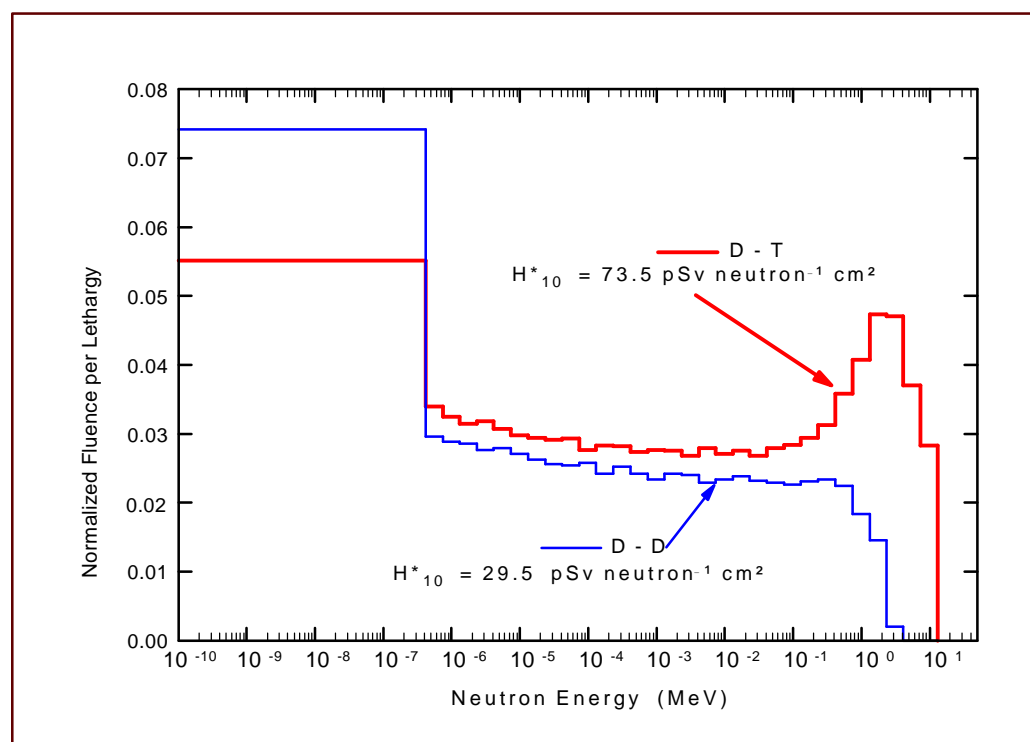Fusion Engineering and Design, <u>28</u>, 534-544 (1995)

Figure 2.1 Neutron spectra measured 1 m outside the north wall of the TFTR Test Cell during operation with D-D and D-T fusion. With neutron energy plotted on a logarithmic scale, the spectra are plotted as fluence per lethargy ($\ln(E_n)$) so that equal areas represent equal fractions of the neutron fluence. H* is the ambient does equivalent.

2.3 NEUTRON SPECTRUM MEASUREMENTS AT DISTANCES UP TO 2 KM FROM A FISSION SOURCE AT THE U.S. ARMY PULSE RADIATION FACILITY

Paul Goldhagen, Marcel Reginatto, Peter Shebell,
Gladys A. Klemic and Nestor Azziz

As part of the reevaluation of the Hiroshima-Nagasaki atomic bomb survivor dosimetry, EML scientists participated in field experiments sponsored by the Defense Nuclear Agency at the Army Pulse Radiation Facility (APRF) of the Aberdeen Proving Ground in May 1992 and June 1993. They were asked to perform neutron field characterizations at various distances from the bare critical assembly (small unshielded fission reactor), which would provide benchmark data on neutron fluences and energy spectra to test long-range neutron transport calculations using codes similar to those applied to the Japanese A-bomb survivor dosimetry. At distances over 1 km from the epicenter of the Hiroshima detonation, where almost all the survivors were, the most recent transport calculations still predict a far lower fluence of thermal-energy neutrons than that determined from activation measurements (Kaul et al., 1994, Straume et al., 1992). Since most of the quantitative knowledge we have about the long-term effects of radiation on people comes from studies of the Japanese atomic bomb survivors, the resolution of this discrepancy is one of the most important problems in radiation dosimetry.

For both the 1992 and 1993 measurements, neutron fluences and energy spectra were obtained using the EML multisphere neutron spectrometer (MNS) with 12 detectors, each of which contains a BF_3-filled pulse ionization chamber. The 1992 measurements were made at distances of 715, 1084, and 1588 m from the critical assembly. In 1993, the distances were 300, 1588, and 1986 m. Neutron spectra were unfolded from the background-subtracted counts in each detector of the MNS (see Summary No. 2.4 for the measured and calculated spectra).

It is difficult to quantitatively compare the calculated spectra with the unfolded measured spectra, so we have made a more direct comparison. We have folded the calculated spectra with our detector response functions, i.e., numerically integrated their product over neutron energy, and compared the results with the measured counts in each detector. The ratios of the calculated to measured (c/m) counts in each detector are shown in Figure 2.2, plotted against range in meters.

In spite of the spread in the c/m count ratios shown in Figure 2.2 (0.65 to 1.68 at the extremes), the agreement is good, especially compared to the factors of 5 to 10 in the c/m activation ratios at Hiroshima. Furthermore, most of the differences at APRF can be understood by taking into account the difference between the environmental conditions (air density and humidity and ground moisture content) during the measurements and those assumed for the calculation. The high c/m ratio at 715 m can be explained by the presence of trees blocking roughly 20-40% of the sky (and skyshine neutrons) at that site.

We conclude that the Hiroshima neutron discrepancy is probably <u>not</u> primarily due to problems with the long-range transport calculations. We also note that the falloff of the thermal neutron fluence with distance we measured at APRF closely matches that for the thermal neutrons at Hiroshima determined from activation measurements. This suggests that many more nearly unmoderated fission neutrons (or at least neutrons above the oxygen cross section window at 2.35

MeV) escaped from the Hiroshima weapon than were assumed in the DS-86 model. If the Hiroshima survivors were exposed to significant numbers of fast neutrons, and not just to gamma rays, estimates of the health risks from exposure to all types of radiation would be affected.

Results of this work were presented at the Fourth Annual Meeting of the Council on Ionizing Radiation Measurements and Standards (November 28-30,1995), and at the American Nuclear Society Topical Meeting "Advancements and Applications in Radiation Protection and Shielding", April 21-25, 1996, in Falmouth, MA, and will be published in its Proceedings.

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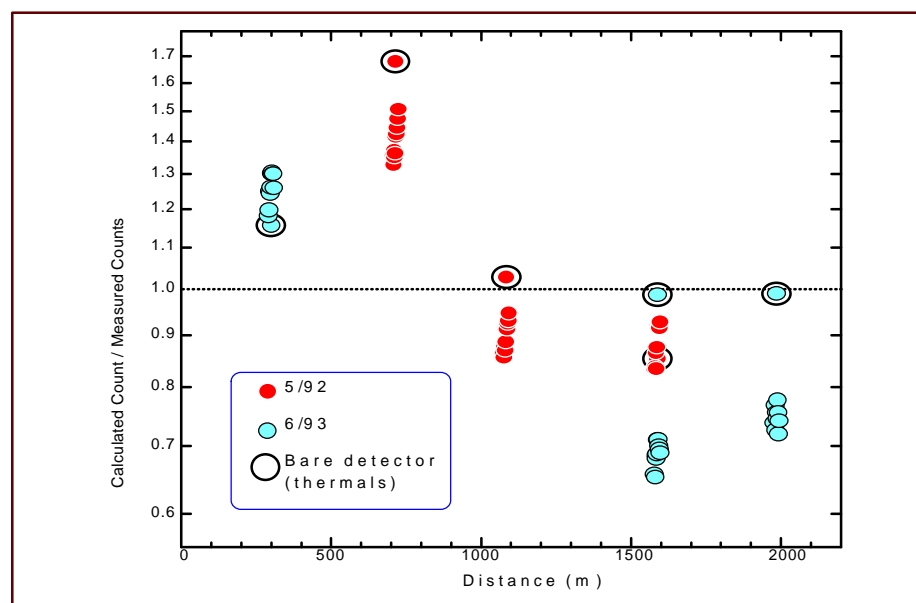Health Physics, 63, 421-426 (1992)

Figure 2.2   Ratio of calculated to measured neutron counts in each sphere detector vs. distance from APRF critical assembly. Calculated counts were computed by folding Kaul's calculated neutron spectra with EML response functions. At each location, smaller spheres (low neutron energy) are plotted to the left of larger spheres (high neutron energy) to produce a slant if there is a trend with neutron energy.

2.4 DECONVOLUTION OF EML MULTISPHERE NEUTRON SPECTROMETER DATA

Marcel Reginatto and Paul Goldhagen

The set of detectors in a multisphere neutron spectrometer (MNS) consists of counters sensitive to slow neutrons which are surrounded by spherical polyethylene moderators of different sizes to produce detectors with different energy responses. For a given detector, the number of counts N is related to the response function R(E) and the neutron fluence f(E) by an integral over the energy E of the form

$$N = \int R(E)f(E)dE .$$

Deconvolution (unfolding) of the data amounts to finding a spectrum f(E) that fits the data for all detectors. The problem of reconstructing the neutron spectrum from a finite number of measurements is mathematically ill posed, and the solution is not unique. Therefore, to find a physically relevant spectrum, *a priori* information must be implemented in the solution method.

A number of mathematical methods have been developed for the deconvolution of neutron spectra. One of the most commonly used unfolding programs is the SAND-II code package (McElroy et al., 1967; Berg, 1968). The calculational procedure used consists of the selection of an initial approximation spectrum (which incorporates *a priori* information), and subsequent perturbation of that spectrum by iterative adjustments to yield a solution spectrum that fits the data.

A version of the neutron spectra unfolding code SAND-II (RSIC code package CCC-112) which runs on personal computers was obtained from the Radiation Shielding Information Center and modified at EML to incorporate the EML MNS detector response functions. This modified code was then used for the deconvolution of data from measurements that EML carried out at the Princeton Tokamak Fusion Test Reactor (TFTR) and at the U.S. Army Pulse Radiation Facility (APRF).

Measurements of leakage neutron spectra were made outside the TFTR Test Cell during deuterium-deuterium (D-D) and deuterium-tritium (D-T) operation (see Summary No. 2.2). After examining spectra from tokamak shielding calculations, we used initial approximation spectra as follows: for D-D fusion, fluence per unit energy proportional to 1/E (constant fluence per unit lethargy) from 0.4 eV to 0.5 MeV then a sharper decrease up to a cutoff at 2.5 MeV; for D-T fusion, fluence per unit energy proportional to 1/E from 0.4 eV to 2.5 MeV then a sharper decrease up to a cutoff at 14.1 MeV. Figure 2.1 shows the results for the unfolded neutron spectra measured 1 meter outside the north wall of the TFTR Test Cell.

The measurements at APRF (see Summary No. 2.3) were made to test long-range neutron transport calculations using codes similar to those applied to the Japanese A-bomb survivor dosimetry. We, therefore, used spectra calculated by the code to be tested as the initial approximation spectra for unfolding measured spectra. The long-range transport calculation we tested was performed by Kaul (1995) using the discrete ordinates transport code DORT. Measured and calculated APRF neutron fluence spectra for the five distances where we made measurements are shown in Figure 2.3 The fluence per lethargy (per joule of fission) has been multiplied by the square

of the range to remove the $1/R^2$ dependence. The Kaul calculated spectra show considerable structure above 100 keV which increases with distance, reflecting the nuclear resonance structure of the oxygen and nitrogen in the air. Such structure appears in the unfolded spectra from SAND II when the calculated spectra are used as initial guesses. Since the resolution of our MNS is no better than 2 to 4 bins per energy decade, the fine-binned output was collected into 4 bins per energy decade, and these wide-binned measured spectra are shown in Figure 2.3. Since our MNS cannot resolve any spectral shape within the thermal-energy region, we have shown no measured thermal spectra. There was generally good agreement between our measured neutron spectra and those from the long-range transport calculation (see Summary No. 2.3).

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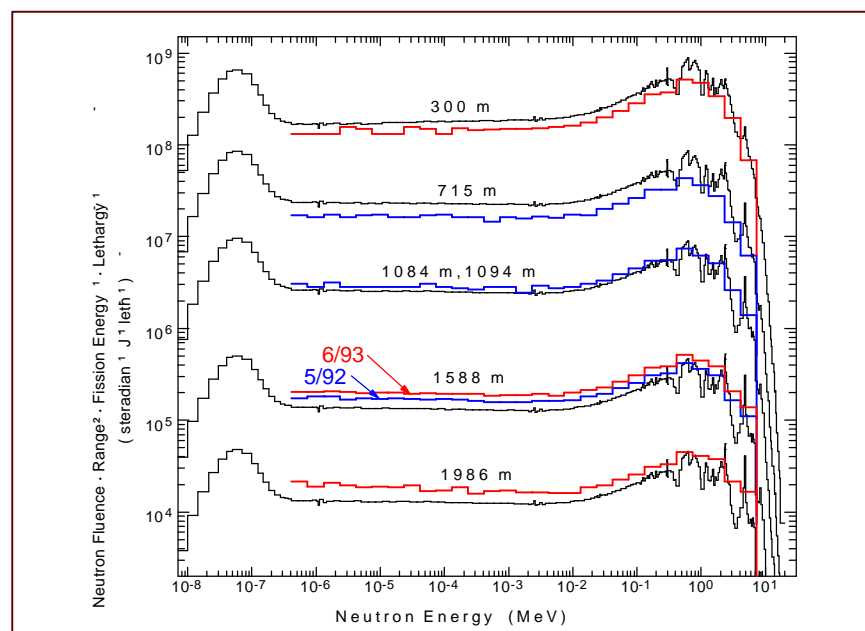U.S. Air Force Weapons Laboratory Report AFWL-TR-67-41 (1967).

Figure 2.3   Measured and calculated APRF neutron fluence spectra. Coarse-binned spectra are unfolded EML measurements. Fine-binned spectra are calculations by Kaul.

2.5 CALCULATION OF MULTISPHERE NEUTRON SPECTROMETER RESPONSE FUNCTIONS

Paul Goldhagen

EML's primary instrument for measuring neutron energy distributions is the multisphere neutron spectrometer (MNS), which is a series of spherical polyethylene moderators of different sizes surrounding counters sensitive to slow neutrons. Determining a neutron energy spectrum from the number of counts in each of the detectors requires knowing each detector's efficiency as a function of energy, called its response function. The slow-neutron counters of the MNS used for the measurements at TFTR and APRF are pulse ionization chambers filled with $^{10}BF_3$ gas at a pressure of about 0.46×10^5 Pa. In 1994 we calculated the response functions of each of the 12 detectors of this MNS using the Monte Carlo particle transport code MCNP (Briesmeister, 1993) and the latest neutron interaction cross sections then available, ENDF/B-V (Goldhagen, 1995). In 1995, the new ENDF/B-VI set of neutron cross sections became available for use with MCNP. We have repeated the response function calculations for detector #1 (the bare $^{10}BF_3$ counter) and detector #6 (100.5 mm diameter, 0.4378 kg moderator) with the new cross sections, and there is no significant difference in the results. We plan to do more calculations with the new cross sections for the detectors with larger moderators.

For measurements of cosmic-ray neutrons on aircraft (see Summary Nos. 2.6 and 2.7), we are using a new MNS (Goldhagen and Van Steveninck, 1995) which has proportional counters filled with ^{3}He at a pressure of 4.0×10^5 Pa as its slow-neutron counters. We have now started to calculate the response functions for the new MNS. In collaboration with Timothy Kniss of the University of Akron, the response of all of the detectors will be calculated up to 20 MeV using MCNP. Figure 2.4 shows the response of a bare ^{3}He counter and the bare $^{10}BF_3$ counter. Also shown is the Maxwellian thermal energy distribution for 20 °C, which is the energy region of most importance. The response of the ^{3}He counter integrated over the thermal distribution is about 6.2 times the thermal response of the $^{10}BF_3$ counter. Neutrons from cosmic rays have energies up to 10 GeV and beyond. To calculate the response of the new MNS at energies above 20 MeV, we will use the Los Alamos High Energy Transport Code (LAHET) in collaboration with scientists at LANL and elsewhere.

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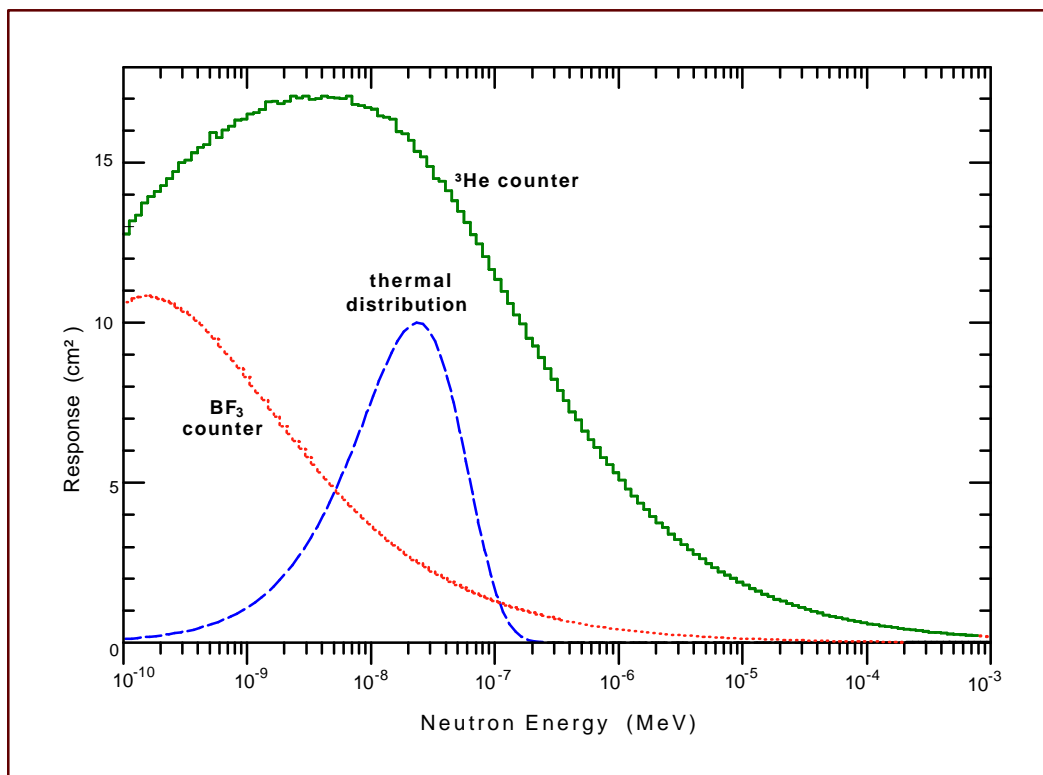US DOE Report EML-571 (1995)

Figure 2.4   Calculated response functions for a bare ^{3}He counter of the new EML multisphere spectrometer and the bare ^{10}BF$_3$ counter of the older spectrometer with ^{10}BF$_3$ counters. The vertical axis units of effective area are equivalent to counts cm^2 neutron^{-1}. The thermal energy distribution for 20˚C (in arbitrary units) is also shown.

2.6 MEASUREMENT OF COSMIC RADIATION ABOARD A CANADIAN FORCES JET AIRPLANE IN FLIGHT

Paul Goldhagen, William Van Steveninck, Alfred J. Cavallo and Peter Shebell

Crews working on jet aircraft are exposed to secondary cosmic radiation and receive one of the highest average dose equivalents of any occupationally exposed group in the western world. In spite of this, the atmospheric ionizing radiation field and dose equivalent rates from it are not precisely known (see Summary No. 2.7). In part, this uncertainty is due to the complexity of the field, which contains virtually every kind of radiation at all energies up to 10 GeV and beyond.

EML has joined the Royal Military College (RMC) of Canada and the Defense Research Establishment, Ottawa, (DREO) in a collaboration to perform cosmic-ray measurements aboard dedicated flights of Canadian Forces CC-137 (Boeing 707) aircraft. The purpose is to characterize the cosmic radiation field in aircraft at altitudes typical of military transport operations and commercial air travel. EML was tasked with measuring the energy spectrum of the neutrons which is the component of the atmospheric radiation field that contributes the greatest uncertainty to the dose equivalent and to estimates of health risk. A successful test flight was made over Canada in December 1994, and transatlantic flights from Trenton, Ontario, to Cologne, Germany, and back were made on May 9 and 11, 1995, with the altitude varied in steps from 10.1 to 12.5 km (33,000 to 41,000 ft).

DREO and RMC flew a variety of radiation detectors. EML's detectors included our new ^{3}He-counter multisphere neutron spectrometer (MNS), a pressurized argon ionization chamber (PIC), thermoluminescent dosimeters (TLDs), and plastic, sodium iodide, and bismuth germanate scintillators with anti-coincidence shells. The anti-coincidence shells discriminate between the charged and neutral components of the incident radiation, while the different materials and densities of the inner scintillators should enable us to separate the nucleons from the leptons and gamma rays. Such measurements, useful in their own right, are needed to correct the MNS results for response to high-energy protons.

The dose rate in air from charged particles and gamma rays measured by the PIC on the transatlantic flights is shown in Figure 2.5 plotted as a function of time. On the return flight, the increasing ionization dose rate as the geomagnetic latitude varied from 53° to 57° N while the altitude was constant at 37,000 and 39,000 ft shows the effect of decreasing geomagnetic shielding. The nearly constant ionization dose rate at constant altitude on the flight to Cologne while the geomagnetic latitude varied from 60° to 70° N shows that there is no further dose rate increase above 60° NGM. This saturation occurs because the earth is shielded from low-energy galactic cosmic rays by the magnetic field of the solar wind plasma that fills the solar system.   The total PIC dose in air for the round trip was 34 ± 5 μGy. (The error will be reduced after calculating the effect of the PIC wall for the electron component as a function of altitude.) The dose measured by our Al_2O_3:C TLDs was 32 ± 6 μGy. Both of these instruments are relatively insensitive to neutrons.

MNS measurements with thousands of counts in each detector were recorded every 150 seconds on the transatlantic flights. At high geomagnetic latitude, the counts in each of the MNS detectors except the one responding to the highest energies were all $1.61 \pm .05$ times higher at

41,000 ft, than at 33,000 ft. This means that the shape of the neutron spectrum below 10 MeV did not change significantly with altitude in this range, while the dose equivalent from that portion of the neutron spectrum increased by a factor of 1.61. Neutron spectra and dose-equivalent rates for each altitude and geomagnetic latitude will be determined when we have completed calculations of the response functions of the MNS (see Summary No. 2.5) and the scintillation counters.

Preliminary results of this work were presented at the Fourth Annual Meeting of the Council on Ionizing Radiation Measurements and Standards (November 28-30, 1995), and at the American Nuclear Society Topical Meeting "Advancements and Applications in Radiation Protection and Shielding", April 21-25, 1996, in Falmouth, MA, and will be published in its Proceedings.
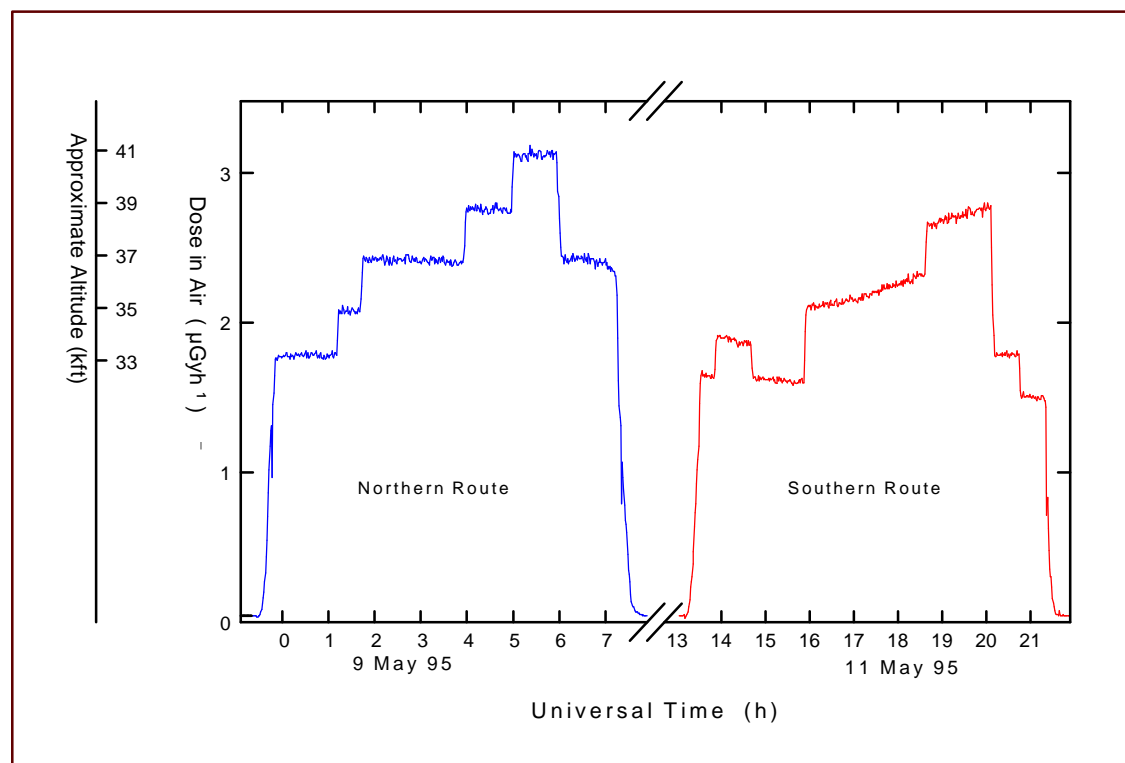

Figure 2.5   Dose rate in air measured by the pressurized argon ionization chamber aboard a Canadian Forces Boeing 707 aircraft as a function of time in hours for the flight from Trenton, Ontario, to Cologne, Germany, on 5/9/95 (northern route) and the return flight on 5/11/95 (southern route).

2.7 ATMOSPHERIC IONIZING RADIATION MEASUREMENTS AT HIGH ALTITUDE USING NASA ER-2 AIRCRAFT

Paul Goldhagen and William Van Steveninck

Research in support of an economically competitive and environmentally safe high-speed civil transport (HSCT) is a high priority within NASA aeronautical programs. Designs are being studied for commercial aircraft that would cruise at altitudes of about 21 km (70,000 feet) - near the Pfotzer maximum of cosmic ray particle flux in the atmosphere. Crews working on such aircraft would be exposed to roughly twice the levels of atmospheric ionizing radiation as present-day air crews, whose dose equivalents are not yet known precisely.

In collaboration with the NASA Langley Research Center (LaRC), in 1994 we examined the radiation safety aspects of the HSCT (Wilson, et al., 1995). Among our conclusions was that there are large uncertainties (plus or minus a factor of 2) in our knowledge of the physical fields for high-energy neutrons and multi-charged ions, which need to be reduced. At NASA's request, the National Council on Radiation Protection and Measurements (NCRP) studied radiation exposure and high-altitude flight and in July 1995 published a Commentary on the subject (NCRP, 1995). Among their eight recommendations were:

(1)   Average absorbed dose rates and their uncertainty in the altitude range of 9,000 to 24,000 m (30,000 to 80,000 ft) require greater specification.

(2)   Additional measurements utilizing currently flying high-altitude aircraft should be made with adequate instrumentation to assist in completion of recommendation (1), (See Appendix A, NCRP Commentary, No.12 for details).

In response to these studies and recommendations, LaRC and EML have developed the atmospheric ionizing radiation (AIR) project. While LaRC develops its AIR environment model computer code, EML will be the principal investigating laboratory for a series of AIR measurements using the NASA ER-2 aircraft as a platform. The primary instruments will be the EML instruments used on the Canadian flights (see Summary No. 2.6), modified to operate at the low air pressure in the ER-2 instrument bays. Results of the measurements will be used as benchmarks to test and validate the AIR environment model code, which can then be used to calculate the dose-equivalent rate at any altitude anywhere on earth at any time in the solar cycle.

It is important to begin the measurements as soon as possible because the solar activity cycle is now at its minimum (resulting in maximum radiation levels) and because decisions concerning the HSCT need to be made within a few years. To make the most complete set of measurements possible with the short development time available, collaborations have been initiated with a number of other radiation measurement groups that have appropriate instruments or are already developing them. Figure 2.6 shows a drawing of the ER-2 and lists the experiments now planned and their locations on the aircraft. Bonner spheres are another name for the detectors of the MNS. The Johnson Space Center (JSC) has a particle telescope that has already been used in space. RMC will fly superheated drop/bubble neutron detectors similar to those it used on the Canadian Forces Boeing 707, and Apfel Enterprises will provide its new REMbrandt™ bubble-detector remmeter. The Boeing Company will

provide a small personal dosimeter and a tissue-equivalent proportional counter (TEPC) similar to the one used by DREO on the 707. DREO's TEPC will also be flown. The two TEPCs will be filled at different pressures to provide different microdosimetric site sizes. The German Air and Space Research Institute (DLR) and Kiel University will send a small particle telescope called DOSTEL and plastic nuclear track detectors (PNTDs). The University of San Francisco and the National Radiation Protection Board (NRPB) of Britain will send different types of PNTDs. This suite of instruments exceeds the recommendations in the Appendix of the NCRP Commentary, and fills all the available space in the ER-2. The first flight is scheduled for Fall, 1996.

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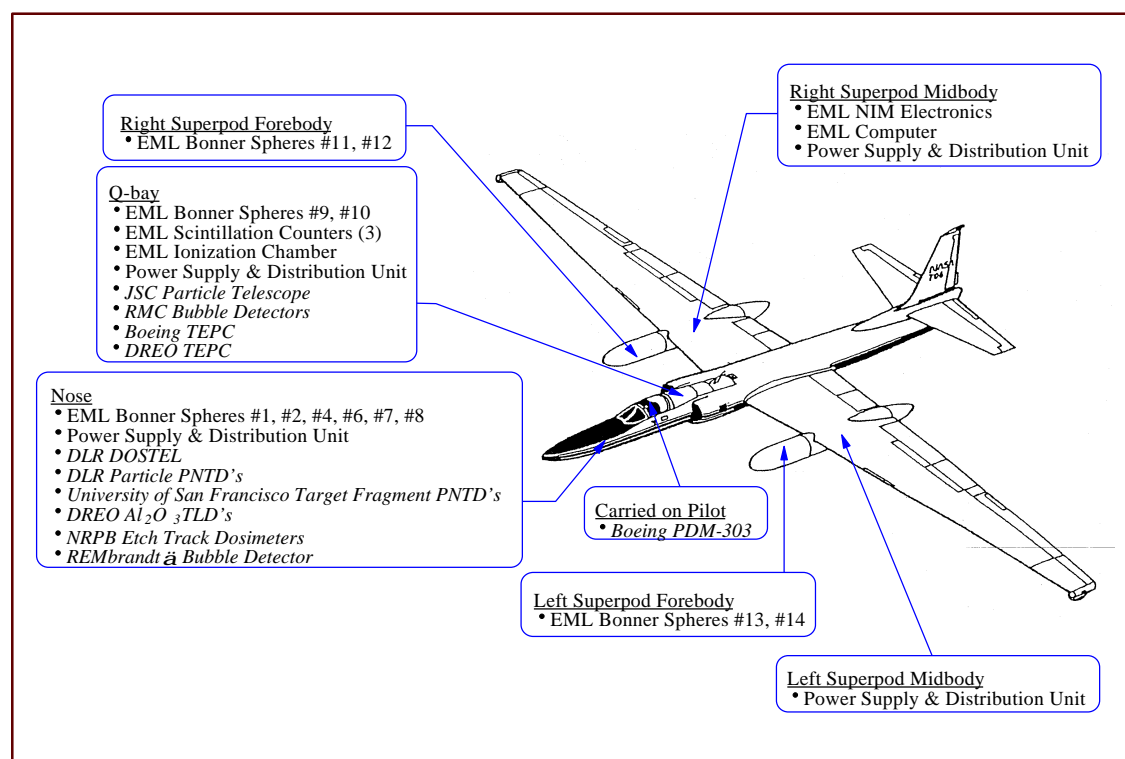NASA Technical Paper 3524, April (1995)

Figure 2.6   Experiment equipment locations on the ER-2 for the high-altitude atmospheric ionizing radiation measurements.

2.8 THE NEUTRON RESPONSE OF Al_2O_3:C , ^{7}LiF:Mg,Cu,P, and ^{7}LiF:Mg,Ti TLDs

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An investigation of the relative neutron:gamma response of some newly developed thermoluminescent dosimeters (TLDs) was completed in 1995 and presented at the 11th International Conference on Solid State Dosimetry in Budapest, Hungary. The recently developed TLDs Al_2O_3:C and ^{7}LiF:Mg,Cu,P have very high photon sensitivity and are, therefore, promising for use in personnel and environmental dosimetry. For potential application in mixed neutron-gamma fields, we investigated the relative neutron:gamma sensitivity ("k_u") of these TLDs compared to that of the widely used ^{7}LiF:Mg,Ti (TLD-700). Narrow-spectra neutrons of energies from 0.33 to 14 MeV produced by a Van de Graaff accelerator at the Radiological Research Accelerator Facility (RARAF) of Columbia University were used to irradiate pairs of TLDs.

The neutron and gamma doses were measured independently using a tissue-equivalent ionization chamber in combination with a compensated Geiger-Mueller detector. To isolate the TLD's response to neutrons, it is necessary to fully account for all gamma dose resulting from photon production in the RARAF target as well as that due to natural background radiation. Control TLDs were used to measure the exposure received in transit and storage, and other controls were used to calibrate the response to gamma radiation using a ^{137}Cs source. TLDs were read out using a manually operated, linearly heated planchet reader. Figure 2.7 illustrates the results. For neutron energies from 0.3 to 6.0 MeV, the k_u of Al_2O_3:C was about one tenth that of TLD-700. The k_u of ^{7}LiF:Mg,Cu,P was about one third that of TLD-700 for the same neutron energy range. All phosphors showed greater response to 14 MeV neutrons, but the relative neutron:gamma sensitivity of the newer phosphors was one third to one fifth that of TLD-700. The results are to be published in Radiation Protection Dosimetry (Klemic, in press).

Reference

Klemic, G. A., N. Azziz, and S.A. Marino
"The Neutron Response of Al_2O_3:C , ^{7}LiF:Mg,Cu,P, and ^{7}LiF:Mg,Ti TLDs"
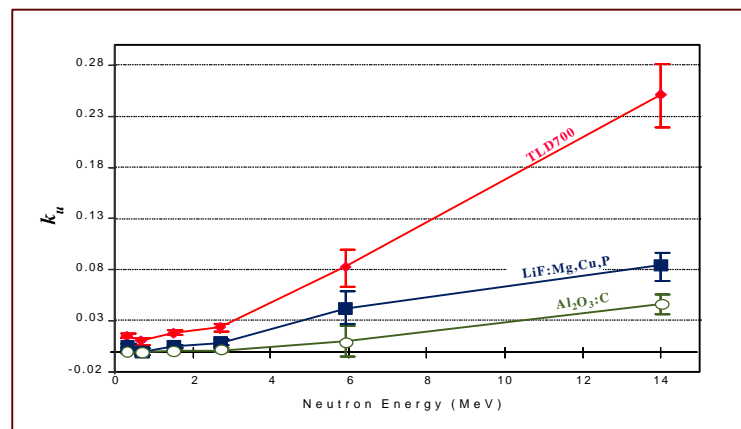Radiation Prot. Dosim., in press

Figure 2.7   Relative neutron sensitivity, k_u (neutron:gamma).